Developing an Eco-Cooperative Automated Control System (Eco-CAC)

PI: Hesham Rakha, Ph.D., P.Eng.
Virginia Tech

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June 19, 2018 – Arlington, VA

Project ID: eems028

Overview

Timeline

- ❑ Start date: 10/1/2017
- ❑ End date: 9/30/2019
- ❑ Percent complete: 40%

Budget

- ❑ **Total project funding:**
  - DOE share: $1,507,197
  - VTTI share: $83,588
- ❑ **Funding for FY 2017:**
  - DOE share: $752,291
  - VTTI share: $84,480
- ❑ **Funding for FY 2018:**
  - DOE share: $754,906
  - VTTI share: $168,068

Project Goals/Barriers

- ❑ Improve energy efficiency of ICEVs, BEVs, PHEVs, and HEVs by integrating multiple connected and automated vehicle (CAV) applications
- ❑ Computational difficulty of accurately modeling and simulating large-scale transportation systems
- ❑ Uncertainty in measuring the energy impact of CAVs in large-scale transportation networks

Collaborators (Not funded by Project)

- ❑ Morgan State University (MSU)
- ❑ Palo Alto Research Center (PARC)

Relevance/Objectives

CAVs are significant emerging technologies that are expected to result in transformative improvements to the transportation system. The main project objective is to substantially reduce vehicle fuel/energy consumption by integrating vehicle control strategies with CAV applications for an affordable, efficient, safe, and accessible transportation future. The project will develop a novel integrated control system that

(1) routes vehicles in a fuel/energy-efficient manner and balances the flow of traffic entering congested regions,

(2) selects vehicle speeds based on anticipated traffic network evolution to avoid or delay the breakdown of a sub-region,

(3) minimizes local fluctuations in vehicle speeds (also known as speed volatility) on freeways and arterials, and

(4) enhances the fuel/energy efficiency of various types of vehicles while focusing on ICEVs, BEVs, HEVs, and PHEVs.

The proposed Eco-CAC system is expected to produce energy/fuel savings of at least 20% in ICEVs, BEVs, PHEVs, and HEVs.

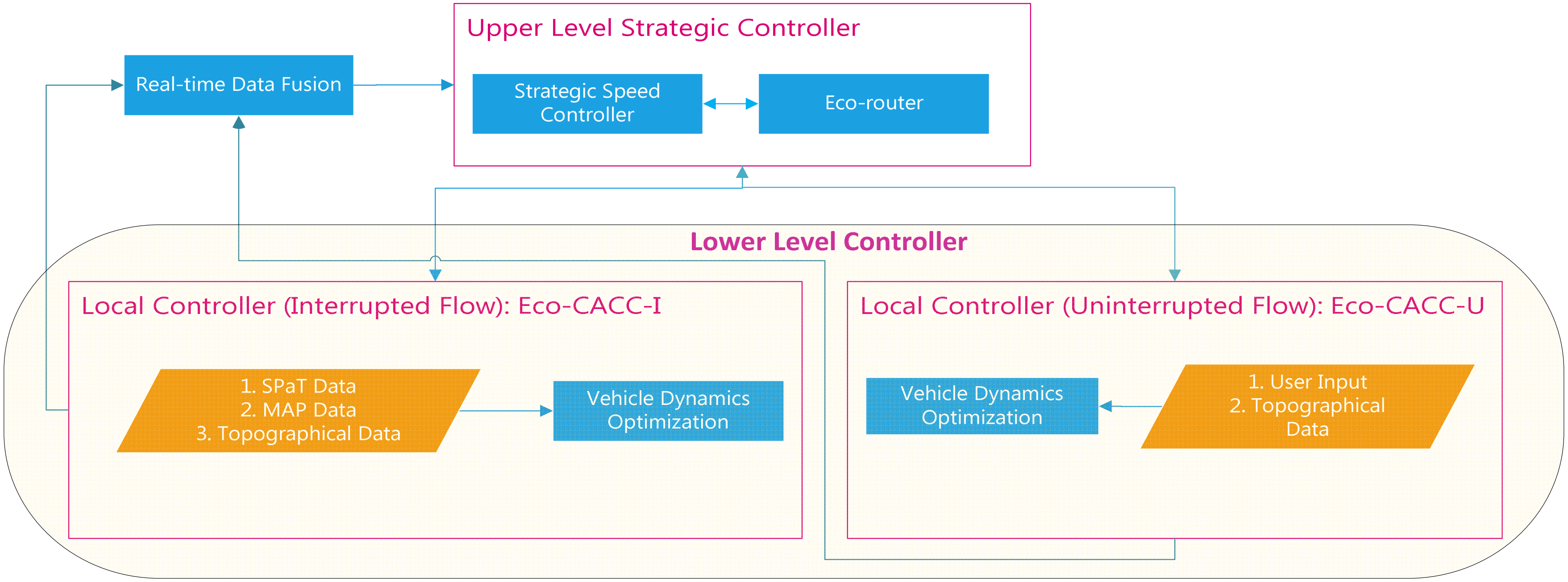
Milestones

Milestones	Planned Completion date	Current Progress – April 2018
Analytical Eco-routing Algorithm Evaluation Complete	November 2018	Developing eco-routing algorithms
Network Monitoring Algorithm Comparison Complete	November 2018	Developing methods to monitor network-wide traffic conditions
Eco-CACC-U Control Strategies Complete	November 2018	Developing Eco-CACC-U control strategies to regulate platooning vehicles
Eco-CACC-U evaluation complete	November 2018	Plan to start July 2018
Integrated Eco-CAC System Assessment Complete	May 2019	Plan to start December 2018
Simulation Model Assessment Complete	June 2019	Plan to start December 2018
Sensitivity Analysis Complete	June 2019	Plan to start April 2019
Eco-CAC Simulation Prototype Evaluation Complete	September 2019	Plan to start April 2019

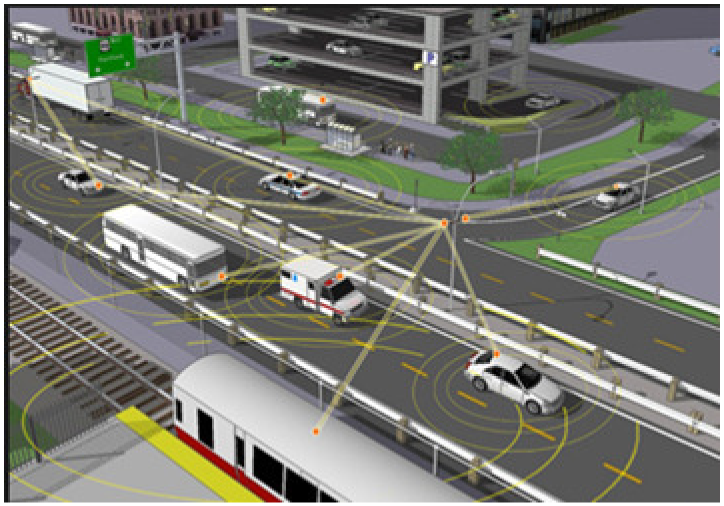
Approach

- Development of the Eco-CAC system will involve the following key steps:

1. Develop a CV vehicle-specific eco-routing controller (12 months).
2. Develop a MFD-based speed harmonization (SPD-HARM) controller to regulate traffic flow (12 months).
3. Develop a vehicle-specific Eco-Cooperative Adaptive Cruise Control-I (Eco-CACC-I) controller (12 months).
4. Develop an Eco-CACC-U controller that provides local longitudinal energy-optimal control in consideration of homogenous and non-homogeneous vehicle platooning (12 months).
5. Integrate the various system components to develop the proposed Eco-CAC system (24 months).
6. Develop an Eco-CAC simulation model and evaluate its potential system-wide impacts (24 months).

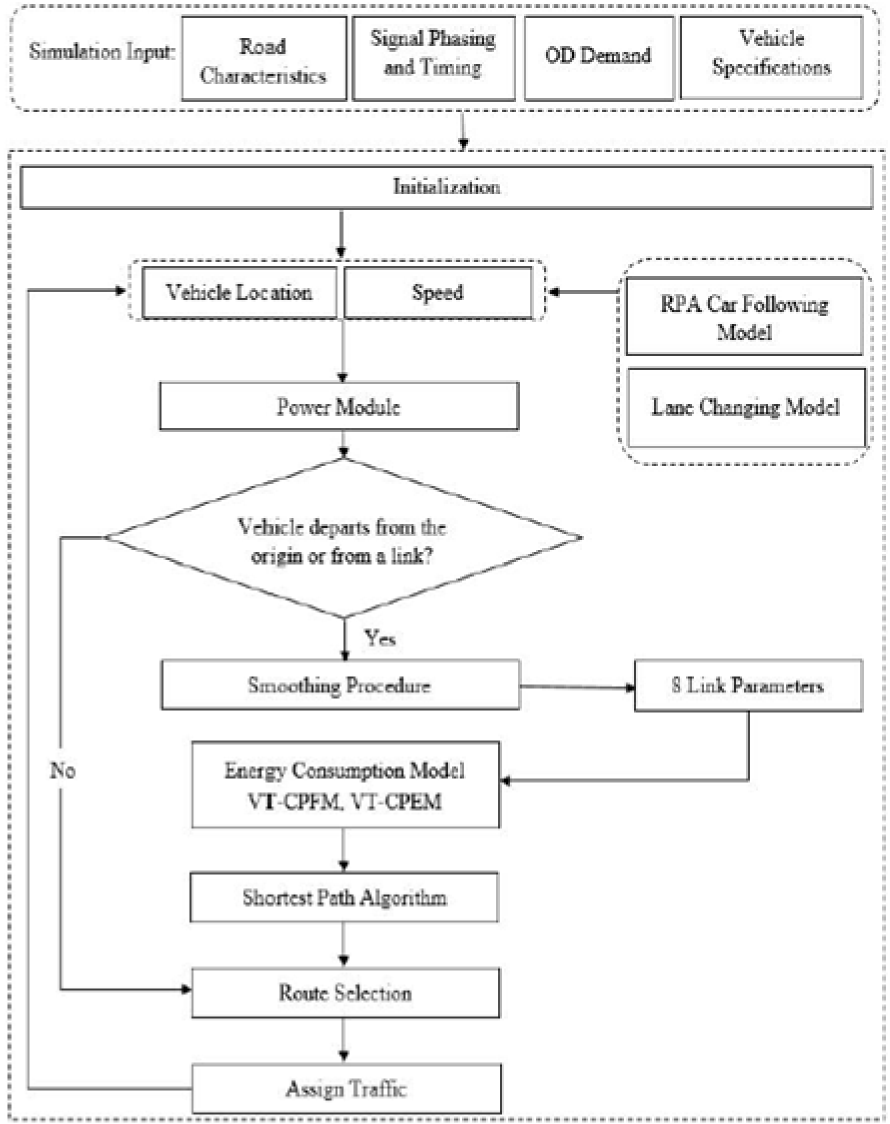


Task 1 – Eco-Routing



Connected vehicle feedback information

$$TT, \sum v^3, \sum v^6, \sum VSP_{rga},$$
$$\sum VSP_{rga}^2, \sum(VSP_{rga} \times v^3),$$
$$\sum(\eta_{rb} \times v^3),$$
$$\sum(\eta_{rb} \times VSP_{rga})$$



Task 1 – Eco-Routing

- Objective function:
  - Min $Z = \sum_l \left(FC_{l,p} x_p + EC_{l,p}(1 - x_p) \right) y_l, \ \forall \, x_p, y_l = 0 \text{ or } 1$

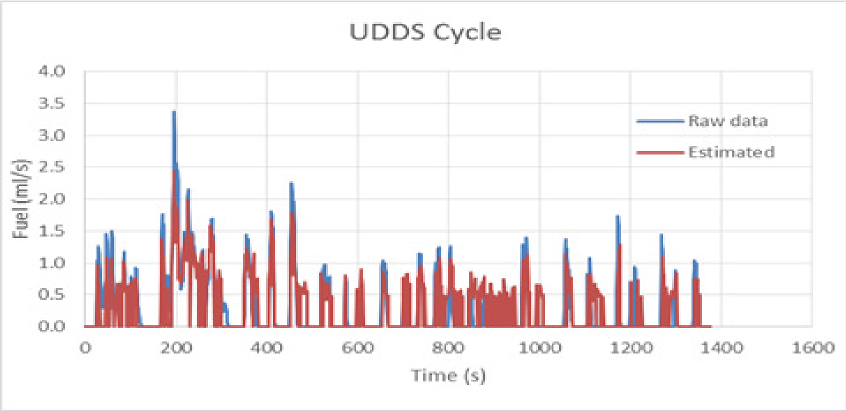
MOEs	Routing Method	Congestion Level								
		5%	25%	50%	75%	100%	125%	150%	175%	200%
Fuel	Proposed Eco-routing (l)	0.472	0.443	0.449	0.452	0.453	0.458	0.464	0.472	0.480
	TT-routing (l)	0.507	0.475	0.474	0.473	0.473	0.473	0.476	0.478	0.483
	Traditional Eco-routing (l)	0.488	0.460	0.465	0.471	0.474	0.485	0.500	0.517	0.530
	Rel. Diff (Pro. Vs. TT) (%)	-6.92	-6.73	-5.26	-4.52	-4.22	-3.16	-2.51	-1.31	-0.76
	Rel. Diff (Pro. Vs. Tra.) (%)	-3.33	-3.66	-3.56	-4.10	-4.50	-5.46	-7.05	-8.78	-9.57
Electric Energy	Proposed Eco-routing (Wh)	91.653	93.698	92.972	91.503	88.907	88.380	86.060	83.395	80.837
	TT-routing (Wh)	120.641	117.369	114.720	115.502	114.109	112.692	111.431	111.286	110.081
	Traditional Eco-routing (Wh)	92.838	100.595	99.796	99.746	99.142	101.561	96.872	88.979	88.136
	Rel. Diff (Pro. Vs. TT) (%)	-23.05	-20.17	-18.96	-20.78	-22.09	-21.57	-22.77	-25.06	-26.57
	Rel. Diff (Pro. Vs. Tra.) (%)	-1.28	-6.86	-6.84	-8.26	-10.32	-12.98	-11.16	-6.28	-8.28
Travel Time	Proposed Eco-routing (s)	217.826	211.751	215.353	218.257	221.077	224.566	230.301	236.548	245.270
	TT-routing (s)	174.792	175.808	177.186	177.629	179.541	180.385	182.988	185.112	188.952
	Traditional Eco-routing (s)	214.014	224.872	228.762	240.489	248.981	260.205	286.571	319.344	352.900
	Rel. Diff (Pro. Vs. TT) (%)	24.62	20.44	21.54	22.87	23.13	24.49	25.86	27.79	29.81
	Rel. Diff (Pro. Vs. Tra.) (%)	1.78	-5.83	-5.86	-9.24	-11.21	-13.70	-19.64	-25.93	-30.50

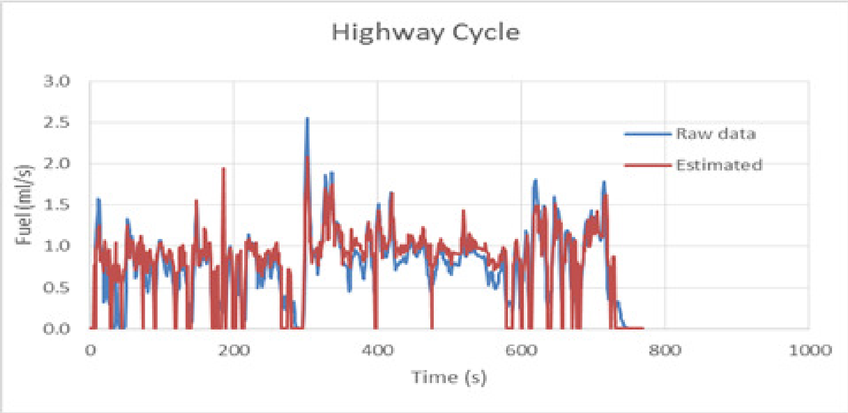
Task 1 – HEV Modeling

- Developed a new power-based microscopic Hybrid Electric Vehicle (HEV) fuel consumption model for a 2010 Toyota Prius

- $FC(t) =$
$$\begin{cases} a + b * v(t) + c * P(t) + d * P(t)^2 & for\ (P > 0\ and\ v \geq 32\ km/h)\ or\ (v < 32\ km/h\ and\ P \geq 10\ kW) \\ Fuel_{EV\_mode} & for\ P \leq 0\ or\ (v < 32\ km/h\ and\ P < 10\ kW) \end{cases}$$

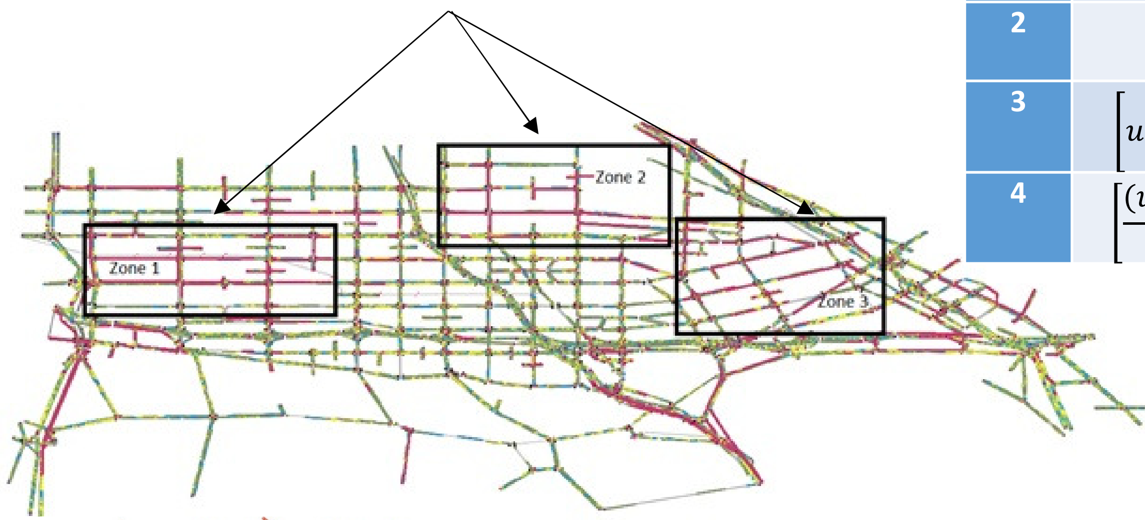
Driving cycles	UDDS (city)	Highway	US06	Steady-state speed	Total
Error Rates	1.5%	6.0%	5.3%	10.1%	1.4%



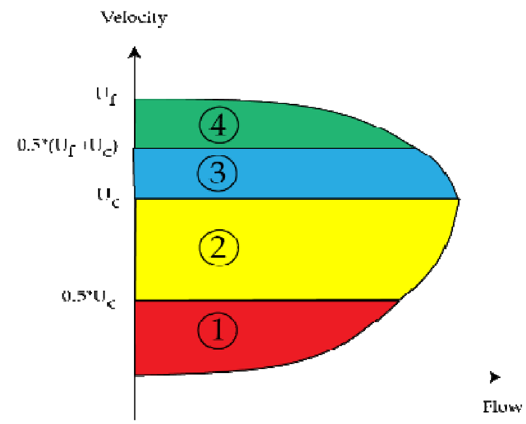


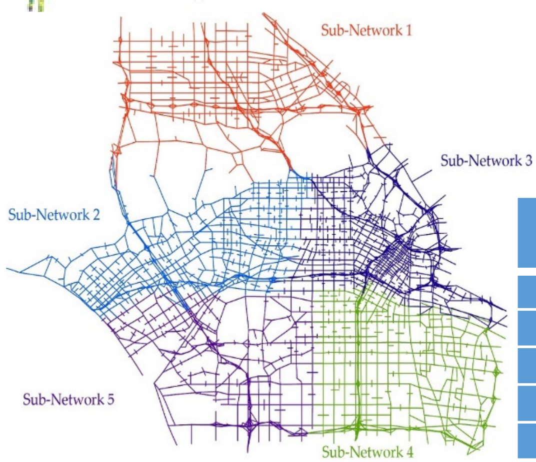
Task 2 - Strategic Control Algorithm Development

Congested Zones: Potential candidates for perimeter control

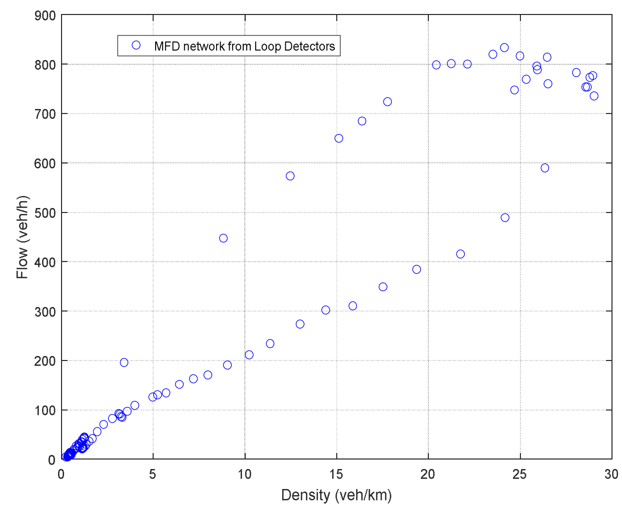


bin	Velocity range
1	$\left[0, \frac{u_c}{2}\right]$
2	$\left[\frac{u_c}{2}, u_c\right]$
3	$\left[u_c, \frac{(u_c + u_f)}{2}\right]$
4	$\left[\frac{(u_c + u_f)}{2}, u_f\right]$

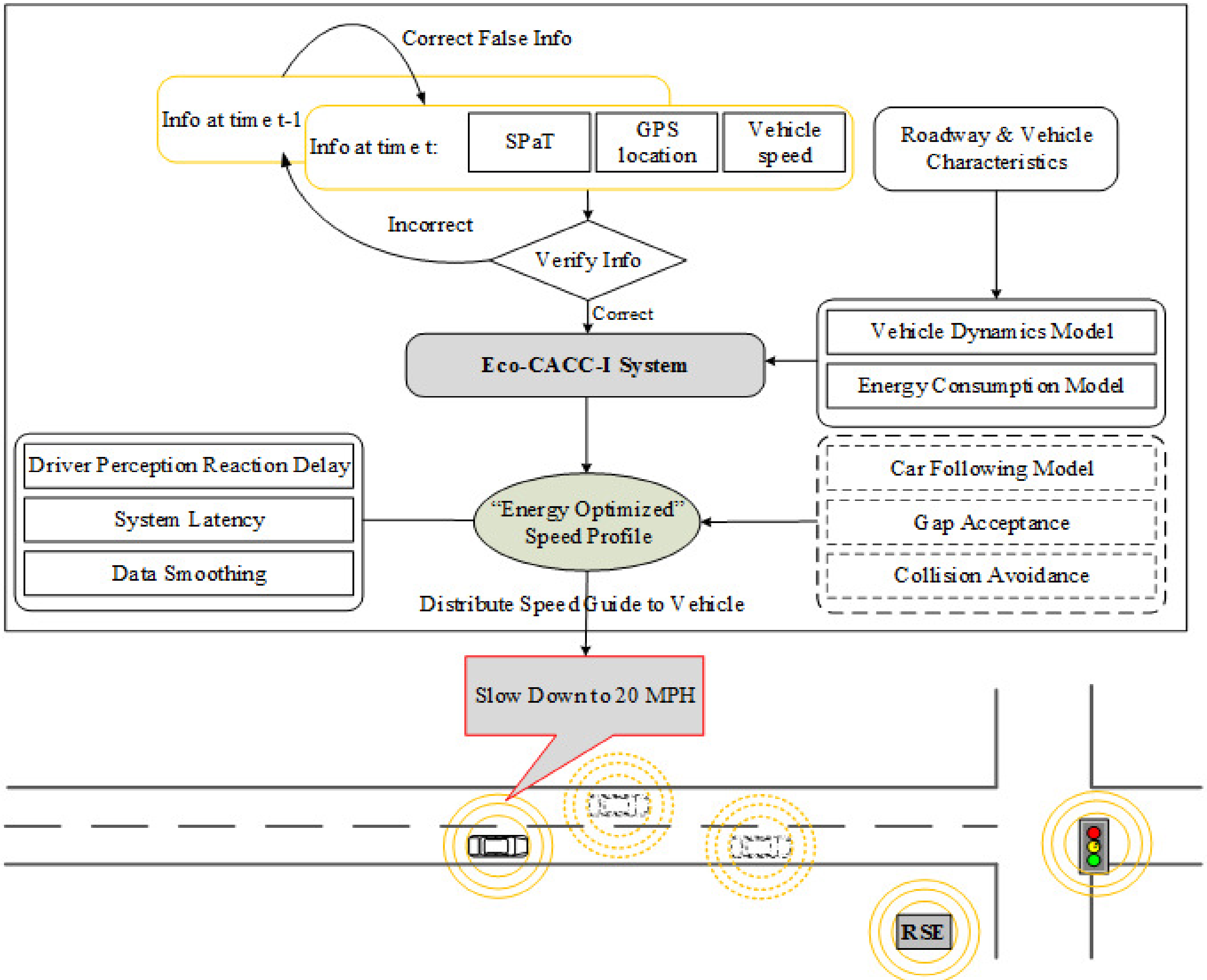




Subnetwork	No. of links	No. of trips	CO_2 (metric tons)
1	1,819	548,131	51
2	2,275	658,725	38
3	3,573	782,812	1894
4	1,834	635,793	1614
5	1,533	528,458	1196



Task 3 - Eco-CACC-I Modeling



Task 3 - Eco-CACC-I Modeling

VIRGINIA TECH

- Vehicle Dynamics Model
  - Acceleration & deceleration (ignore R_a in deceleration)
- Energy Consumption Model
  - The Comprehensive Power-based Electric Vehicle Energy Consumption Model (CPEM)
- Energy-optimized Trajectory
  - Objective function

$$min \int_{t_0}^{t_0+T} EC\big(u(t)\big) \cdot dt$$

$$u(t+\Delta t) = u(t) + 3.6\frac{F(t) - R(t)}{m}\Delta t$$

$$F = \min\left(3600 f_p \beta \eta_d \frac{P}{u}, m_{ta} g \mu\right)$$

$$R = \frac{\rho}{25.92} \mathrm{C}_d \mathrm{C}_h \mathrm{A}_f u^2 + mg\frac{c_{r0}}{1000}(c_{r1}u + c_{r2}) + mgG$$

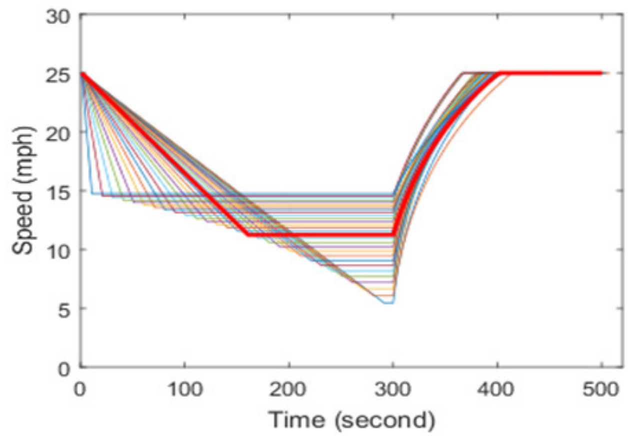
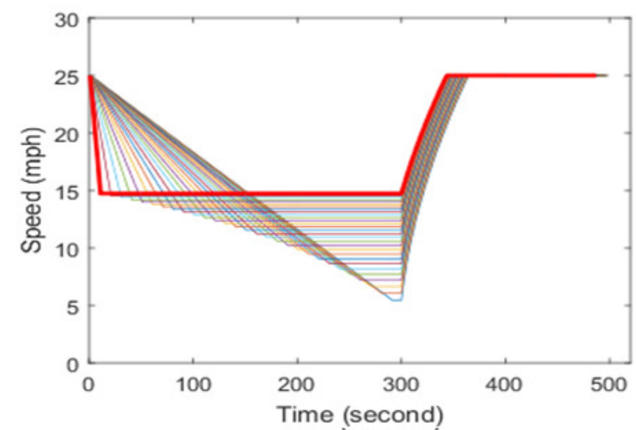
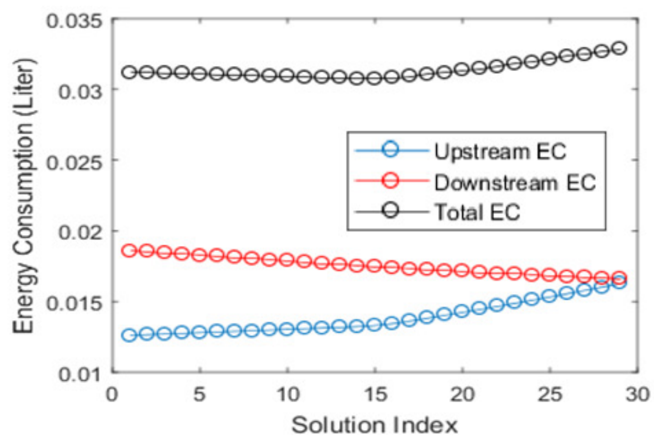
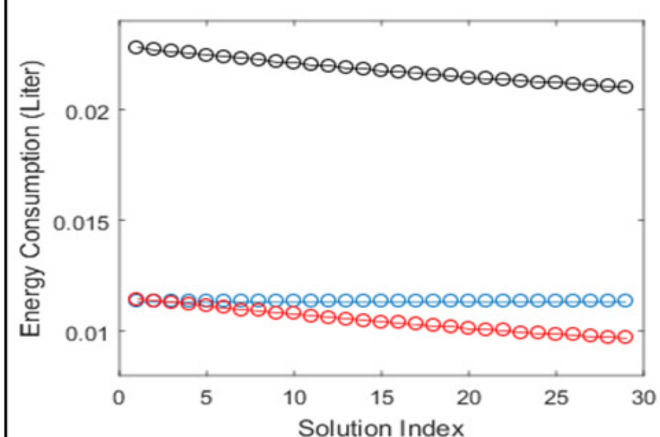
$$EC(t) = \int_0^t P_{Battery}(t) \cdot dt$$

$$P_{Battery}(t) = \left(P_{Wheels}(t) \cdot \frac{\eta_{rb}(t)}{\eta_D \cdot \eta_{EM}} + P_A\right) \cdot \frac{1}{\eta_B}$$

$$P_{Wheels}(t) = \big(ma(t) + R(t)\big) \cdot u(t)$$

$$\eta_{rb}(t) = \begin{cases} 1 & \forall\, P_{Wheels}(t) \geq 0 \\ \left[e^{\left(\frac{\lambda}{|a(t)|}\right)}\right]^{-1} & \forall\, P_{Wheels}(t) < 0 \end{cases}$$

Task 3 - Eco-CACC-I Modeling

<table>
<tr><th></th><th>Uphill (3%)</th><th>Downhill (-3%)</th></tr>
<tr><td>Speed Profile</td><td></td><td></td></tr>
<tr><td>Energy Consumption</td><td></td><td></td></tr>
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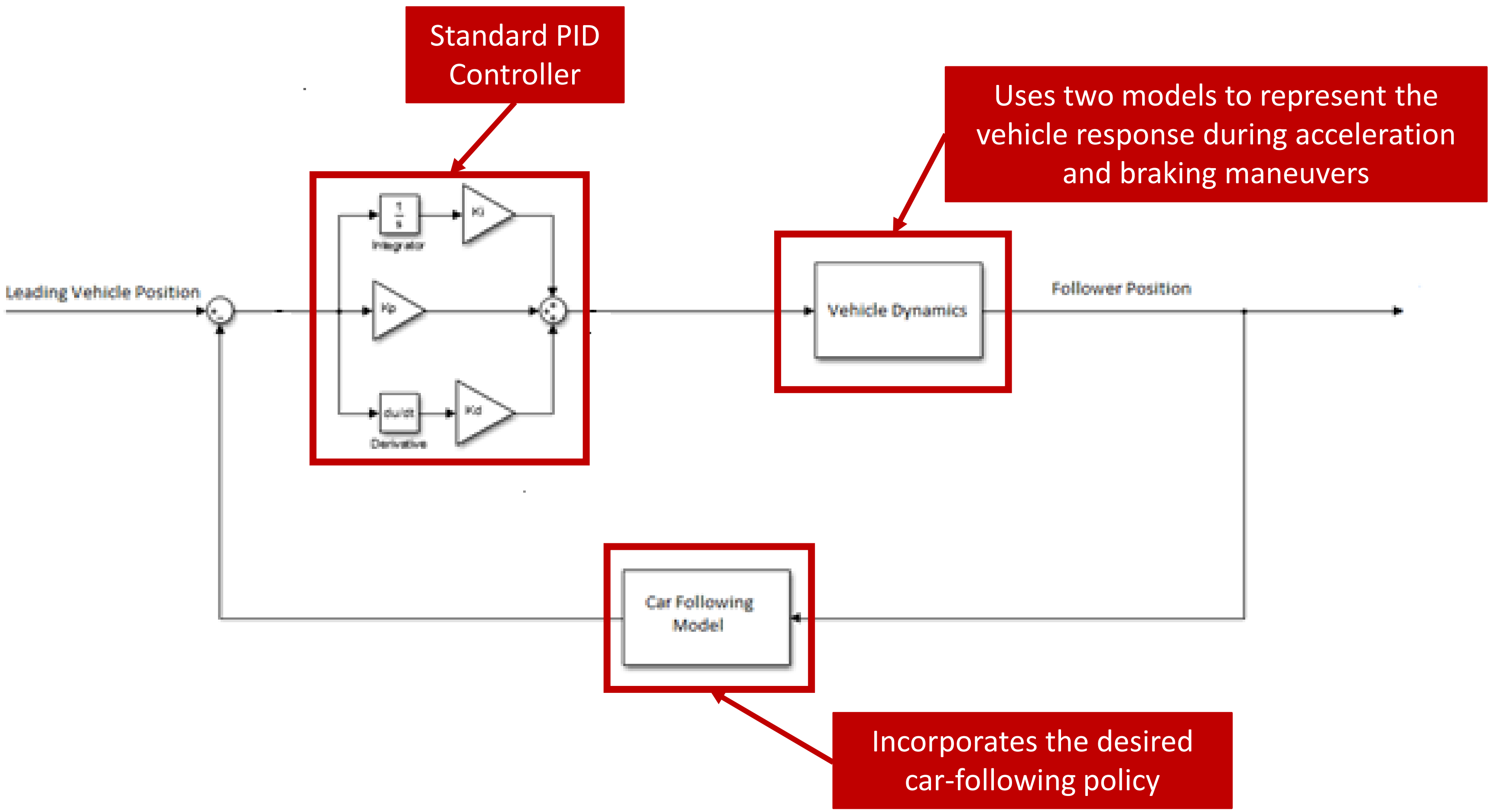
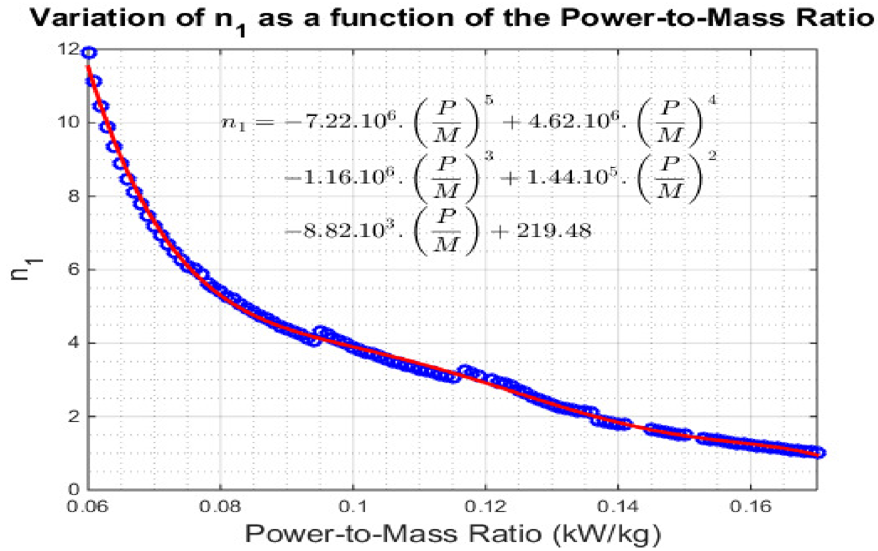
- 2015 Honda Fit – speed limit: 25 mph; red indication offset: 30 sec.

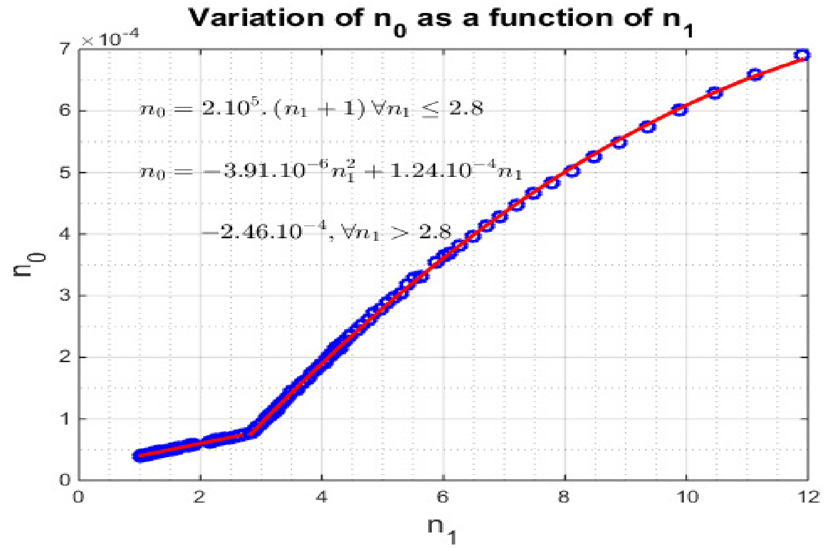
Task 4 - Eco-CACC-U Modeling

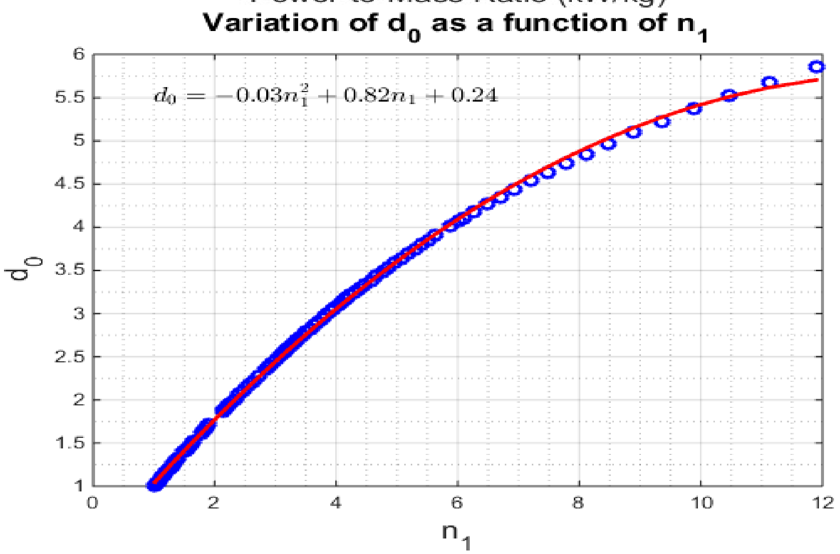
- Developed a preliminary design for the Eco-CACC-U

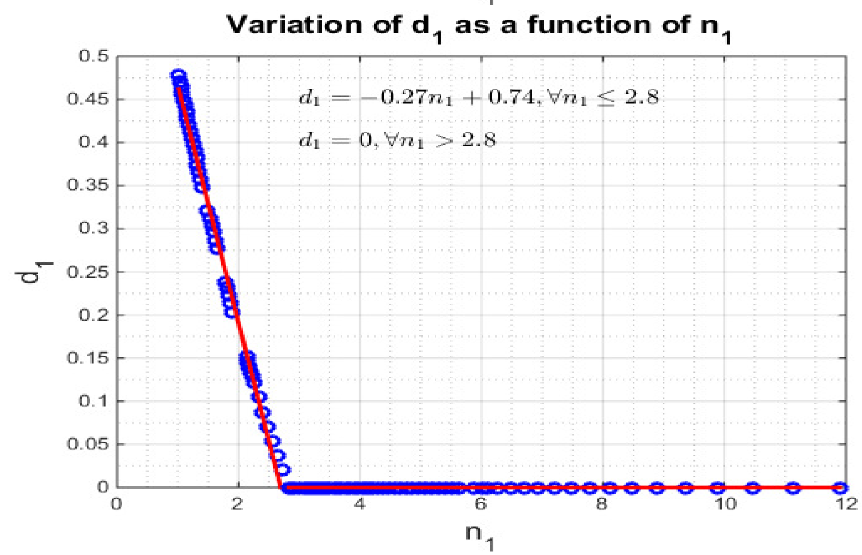


Task 4 - Eco-CACC-U Modeling



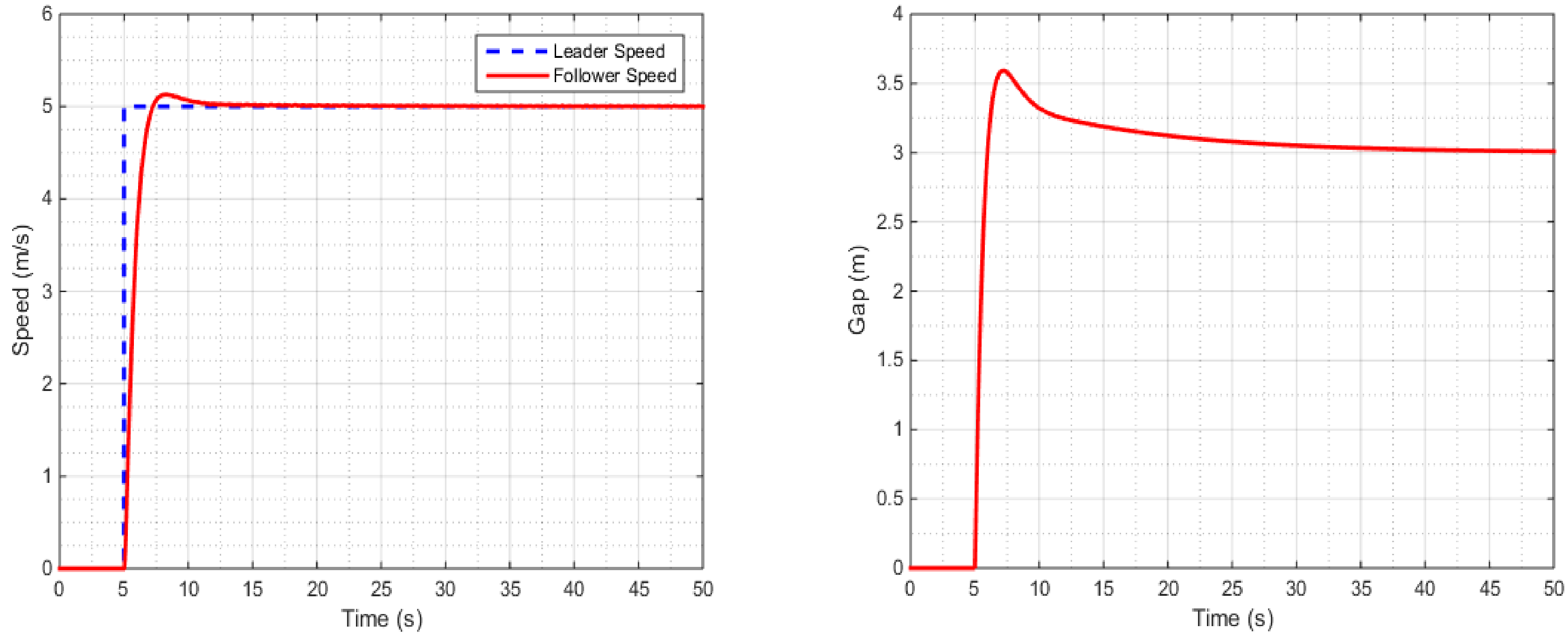






Task 4 - Eco-CACC-U Modeling

- Example Application of proposed acceleration model:
  - Power-to-Mass ratio of following vehicle is 0.15 kW/kg;
  - Desired time headway to maintain with the leader is 0.6 s



Responses to Reviewers' Comments

- This project is a new start and thus it was not reviewed last year.

Collaborations and Coordination

- No collaboration partners within the DOE funding given that the team consists of a single institution.
- Collaboration with Morgan State University (MSU) as part of the University Mobility and Equity Center (UMEC)
  - Testing our Eco-CACC-I system on test subjects in a driving simulator
- Collaboration with the Palo Alto Research Center (PARC) on the large-scale transportation system modeling and modeling of the LA network
  - ARPA-E project

Remaining Challenges and Barriers

- While single CAV applications can improve the performance of a local intersection or a short highway section, maximizing the potential benefits requires systematically optimizing and integrating these applications to develop a fully-integrated traffic controller.
- The study will identify the value and productivity derived from new integrated CAV mobility technologies.
- The study will extend disaggregated systems to a comprehensive, network-wide eco-CAC system. This project will develop a prototype model using microscopic traffic simulation and a communication simulator to evaluate the network-wide impacts of the proposed Eco-CAC system.

Proposed Future Work

- Ongoing work – FY18
  - Eco-Routing System Development
  - Strategic Control Algorithm Development
  - Eco-CACC-I Development
  - Eco-CACC-U Development
- Future work - FY18 and FY09
  - Integrated Eco-CAC System Assessment (December 2018)
  - Simulation Model Assessment (December 2018)
  - Sensitivity Analysis (April 2019)
  - Eco-CAC simulation prototype evaluation (April 2019)
- Any proposed future work is subject to change based on funding levels.

Summary

- Budget Period 1 tasks are on track for evaluation during 4th quarter of 2018.

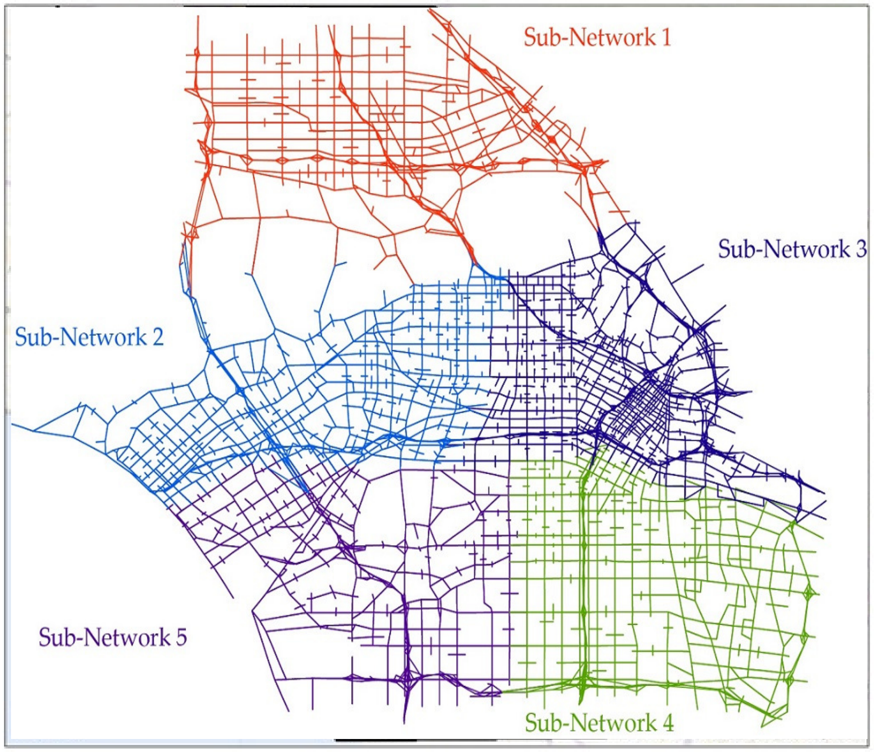
Tasks	Percentage completion	Key Technical Results
Eco-routing model development	40%	• Developed Eco-routing models for ICEVs and BEVs • Developed HEV energy model
Network monitoring algorithm development	40%	• Testing LA downtown network • MFD to monitor the state of a transportation network
Eco-CACC-I controller development	40%	• Developed Eco-CACC-I control model for BEVs
Eco-CACC-U controller development	35%	• Developing car-following module for platooning

Technical Backup Slides

Task 2 - Strategic Control Algorithm Development

- Greater LA is divided into 5 subnetworks
  - More than 11,034 links
  - 3,153,919 vehicle trips

Subnetwork	No. of links	No. of trips	CO_2 (metric tons)
1	1,819	548,131	51
2	2,275	658,725	38
3	3,573	782,812	1894
4	1,834	635,793	1614
5	1,533	528,458	1196



- We consider sub-network 1 for the study of perimeter control
  - We simulate sub-network 1 using INTEGRATION
    - Control is implemented to disperse congestion

Task 2 - Strategic Control Algorithm Development

- Constructing the MFD requires an estimate of the LMP of CVs
  - Requires estimating an O-D from fixed sensor counts
  - Identify optimum location of link counts
    - Calculate a weighted score for candidate links
      - $FinalScore_i = \sum_{j=1}^{3} Weight_j \times Score_{i,j}$
  - Possible Contributing Factors
    - Spatial locations of the links – Cover as much area as possible
    - Inter-correlation of traffic conditions on such links - Getis-Ord Gi Analysis to calculate the correlation of traffic density and the spatial clustering index
      - $G_i^* = \dfrac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j} x_j}{S\sqrt{\dfrac{[n \sum_{j=1}^{n} w_{i,j}^2 - (\sum_{j=1}^{n} w_{i,j})^2}{n-1}}}$
    - The comprehensiveness of such links to represent of the overall traffic pattern
      - The frequency of selected links traveled by probe vehicles